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MATERIALS PROCESSING

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OPTIMAL LASER-PROCESSING REGIME FOR GLASS AND CERAMIC MATERIALS

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An analytical relation for calculating the vaporized material mass per unit energy input is obtained in a one-dimensional model of the vaporization of an absorbing layer of material as a result of the 'instantaneous' deposition of energy by a laser pulse. This relation makes it possible to determine the optimal regime for processing glassy and ceramic materials possessing volume absorption of laser radiation. The adequacy of the computational model is checked experimentally.

Key words: laser processing, vaporization of material, optimal regime, glass, ceramic.

Continuous wave or pulsed lasers are now used for processing glass, ceramic and semiconductor plates [1 – 4]. One method of laser processing of materials is scribing. If the properties of the material do not permit processing by means of thermal cleavage [1] or cleavage on the irradiated surface side [5], then scribing is conducted in a vaporization regime. As a rule, the processed materials possess volume absorption of the exciting radiation. To determine the optimal processing regimes we shall examine the solution of the problem of vaporization of the absorbing layer of material. The thermophysical and optical properties of the plate material are assumed to be independent of temperature.

If

$$R_s \gg \sqrt{a\tau} \quad \text{and} \quad \chi\sqrt{a\tau} \ll 1, \tag{1}$$

where R_s is the radius of the laser spot, a is the thermal diffusivity of the material, τ is the duration of the laser pulse and χ is the absorption coefficient of the plate material at the wavelength of the laser radiation, then the problem of the vaporization of the absorbing layer of the material with 'instantaneous' energy deposition can be regarded as one-dimensional. The physical meaning of the conditions (1) is as follows:

– the laser pulse heats the material by direct penetration into the material;

– heat removal from the heated layer over the laser pulse time can be neglected.

For example, for most glassy materials in which the thermal diffusivity is less than 10^{-2} cm^2/sec, the conditions (1) hold during the laser pulse duration 10^{-3} sec for $R_s > 0.03$ cm and $\chi < 20$ cm^{-1}. The power density of the laser radiation in the material is determined by Bouguer's law [1]

$$q(x, t) = (1 - R)q_0(t)e^{-\chi x}, \tag{2}$$

where q_0 is the power density of the incident laser radiation; R is the reflection coefficient; χ is the absorption coefficient of the material at the wavelength of the laser radiation; t is the time; and, x is the coordinate measured from the surface into the material.

If absorbed energy in the section x is greater than the specific energy of vaporization Q of the material, i.e.,

$$(1 - R)\chi W e^{-\chi x} \geq Q, \tag{3}$$

where $W = \int_0^\tau q_0(t)\mathrm{d}t$ is the energy density of the laser radiation, then vaporization of the absorbing layer will occur. We obtain from Eq. (3) the following relation for the thickness of the vaporized layer:

$$x = \frac{1}{\chi}\ln\frac{(1-R)\chi W}{Q}. \tag{4}$$

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The mass of the vaporized material per unit area will be

$$m = x\rho = \frac{\rho}{\chi}\ln\frac{(1-R)\chi W}{Q}. \quad (5)$$

where ρ is the density of the material.

The specific (per unit energy input) mass of the vaporized material will be

$$m_{\text{sp}} = \frac{m}{(1-R)W} = \frac{\rho}{(1-R)\chi W}\ln\frac{(1-R)\chi W}{Q}. \quad (6)$$

Analysis of the Eq. (6) for the extremum shows that the specific mass of the vaporized material has a maximum for $\frac{(1-R)\chi W}{Q} = e$ (e is the base of the natural logarithm), and m_{sp} at the point of the maximum is a constant depending on the specific material and equals $(m_{\text{sp}})_{\max} \approx 0.368\rho/Q$. The thickness of the vaporized material will be $1/\chi$. A subsequent increase of the energy density will result in a thicker evaporated layer but the specific mass of the vaporized material will decrease.

The minimum energy density resulting in vaporization of the material is determined from Eq. (3) for $x = 0$ and equals

$$W_{\min} = \frac{Q}{(1-R)\chi}. \quad (7)$$

To check the adequacy of the computational model the action of the 1.06 μm radiation from a GOS-1001 laser with pulse duration 10^{-3} sec on a plate of ZHZS12 colored optical glass was investigated. The absorption coefficient of ZhZS12 glass at this wavelength is 10 cm^{-1} [6], and the specific energy of vaporization about 4×10^4 J/cm^3 [7]. The laser radiation was focused into a 2 mm in diameter spot on a plate. The following were measured in the experiment:

– the energy of the laser radiation (using Ophir 12A-P thermocouple);

– the diameter of the laser spot in the plane of the experimental sample (Ophir SP620U laser profile analyzer);

– the duration of the laser pulse (FD2 laser diode and Tektronix TPS 2024B oscillograph);

– the pre- and post-irradiation mass of the sample (VL-200 analytical balance).

The energy density of the laser radiation and the specific mass of the vaporized layer of the material were calculated from the measured values. Each experimental point was obtained by statistical analysis of ten tests. The computational results obtained using the relation (6) and the results of the experiments are presented in Fig. 1. The initial data for the calculations were taken from [6, 7].

Analysis of the results shows that as the energy density increases from the value $W_{\min}$ to $2.72W_{\min}$ the specific mass of the vaporized material increases rapidly, reaching the maximum value, and then decreases. This behavior of the specific mass of the vaporized material versus the energy density is explained by the fact that essentially

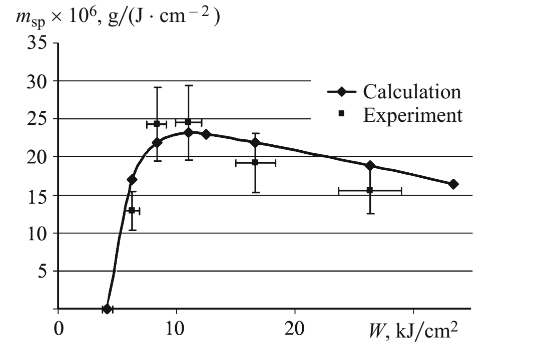

Fig. 1. Specific mass m_{sp} of vaporized material versus the input laser radiation energy density W.

$$m_{\text{sp}} = \frac{\rho}{Q}\frac{\ln\alpha}{\alpha}, \quad (8)$$

where $\alpha = \frac{(1-R)\chi W}{Q}$.

The equation (8) holds for any material with exponential absorption of radiation.

A nearly optimal scribing regime is one where laser radiation with energy density corresponding to the value $(2-4)W_{\min}$ is used for material processing. In this range of energy densities the change in the specific mass of the vaporized layer does not exceed 6%. If scribing depth greater than $1/\chi$ is required, then several laser pulses must be used.

It is evident from the figure that the experimental data agree satisfactorily with the computational results.

In summary, an analytical relation for determining the optimal scribing regime for glassy and ceramic materials possessing volume absorption of laser radiation was obtained and the adequacy of the computational model was confirmed.

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